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King, D, Males, A orcid.org/0000-0002-7250-8300, Davies, G J orcid.org/0000-0002-7343-776X et al. (1 more author) (2019) Molecular mechanisms regulating O-linked N-acetylglucosamine (O-GlcNAc)–processing enzymes. *Current Opinion in Chemical Biology*. pp. 131-144. ISSN 1367-5931

<https://doi.org/10.1016/j.cbpa.2019.09.001>

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Molecular mechanisms regulating O-GlcNAc processing enzymes

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Abstract

The post-translational modification of proteins by O-linked N-acetylglucosamine (O-GlcNAc) dynamically programs cellular physiology to maintain homeostasis and tailor biochemical pathways to meet context-dependant cellular needs. Despite diverse roles for O-GlcNAc, only two enzymes act antagonistically to govern its cycling; O-GlcNAc transferase (OGT) installs the monosaccharide on target proteins and O-GlcNAc hydrolase (OGA) removes it. Recent literature has exposed a network of mechanisms regulating these two enzymes to choreograph global, and target-specific, O-GlcNAc cycling in response to cellular stress and nutrient availability. Herein, we amalgamate these emerging mechanisms from a structural and molecular perspective to explore how the cell exerts fine control to regulate O-GlcNAcylation of diverse proteins in a selective fashion.

Introduction

The covalent attachment of β -linked *N*-acetylglucosamine to the hydroxyl group of protein serine and threonine residues has been identified on hundreds of nucleocytosolic and mitochondrial proteins, and is abundant throughout all multicellular eukaryotes [1]. The donor substrate for OGT catalyzed O-GlcNAcylation is uridine diphosphate *N*-acetylglucosamine (UDP-GlcNAc), the biosynthetic product of the nutrient responsive hexosamine biosynthetic pathway (HBSP). Protein O-GlcNAc levels are thus tied to nutrient status through HBSP flux, facilitated by the reversible nature of O-GlcNAc that can be installed and removed multiple times during the lifespan of a protein [1]. O-GlcNAc is being found to modulate proteins in an increasing variety of ways including manipulation of: protein function, protein-protein interactions, protein localization, and protein stability (reviewed in [1]). Additionally, O-GlcNAc has the potential to compete directly and indirectly with phosphorylation sites and may agonize or antagonize other post-translational modifications (PTMs), including ubiquitinylation, sumoylation, and acetylation (reviewed in [1]), although relatively few such interactions have been demonstrated. Nevertheless, taken together, dynamic cycling and interplay with other PTMs make O-GlcNAc ideally suited as a nutrient and stress responsive molecular switch.

Various noxious stimuli including heat shock, nutrient depletion, ER dysfunction, and redox imbalance cause fluctuations in global O-GlcNAc levels to help combat these stressors. Aberrant O-GlcNAc cycling has been linked to chronic human diseases, including neurodegeneration, cancer, diabetes mellitus, and X-linked intellectual disability (XLID) [2,3]. The diverse physiological roles of O-GlcNAc and its emerging importance in human health underscore the importance of uncovering the complex molecular mechanisms orchestrating its installation and removal on protein targets, both in normal physiology and pathological states.

Herein, we summarize the biochemical underpinnings of the O-GlcNAc modification and integrate salient concepts pertinent to its regulation. Notably, the O-GlcNAc enzymes have evolved elaborate multi-domain structures that are ideally suited to enable the integrated fine-tuning of their function by diverse regulatory mechanisms. Accordingly, we start with an overview of their structures and then consolidate select recent literature illuminating key regulatory mechanisms that define the abundance, localization, and specificity of the O-GlcNAc

cycling enzymes. We focus on emerging interconnected regulatory processes including: subcellular localization, PTMs, protein-protein interactions, metabolic control, and transcriptional and post-transcriptional regulation (Figure 1). Throughout, we highlight current paradigms and raise key unanswered questions. Due to space constraints we regrettably make various omissions to focus on the selected literature most relevant to this topic.

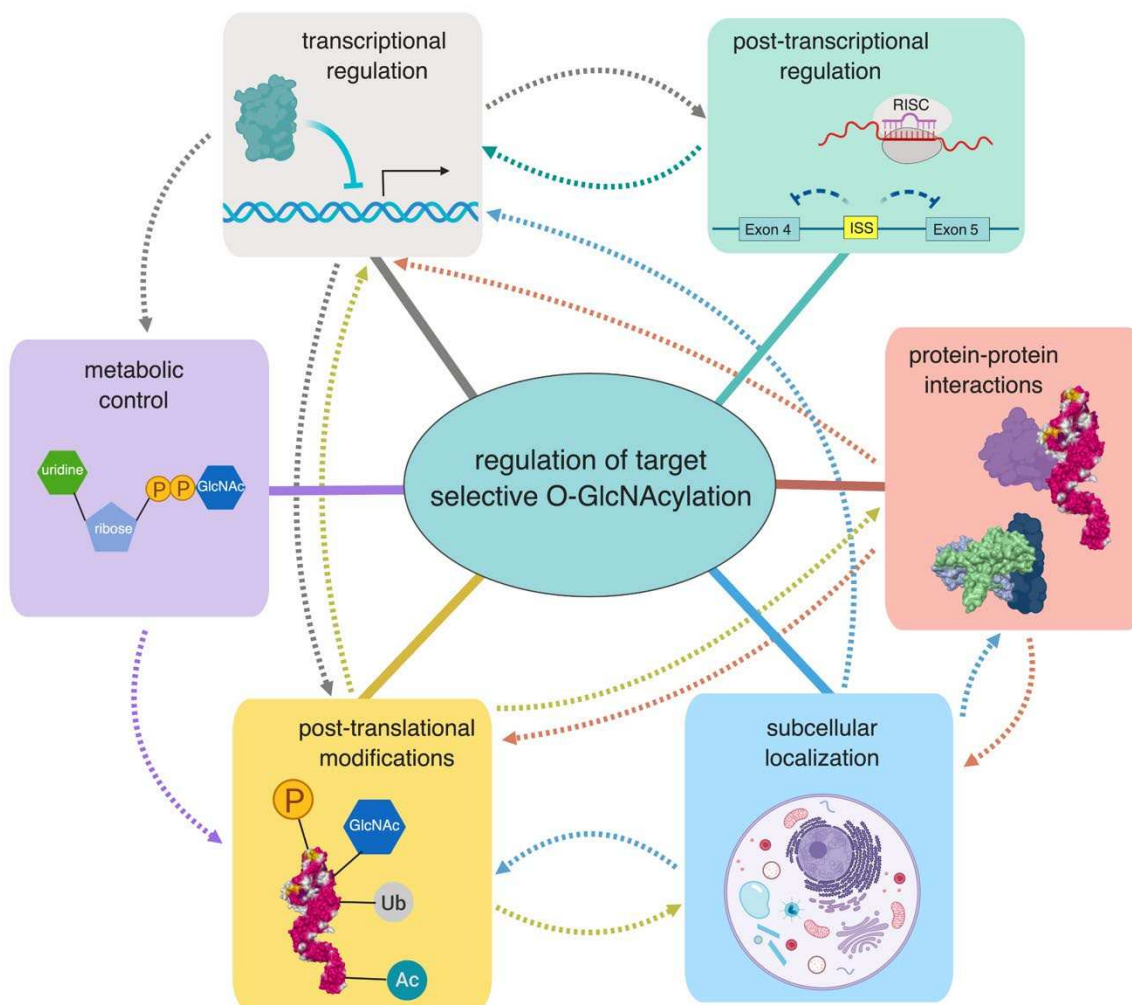


Figure 1. Concept map depicting the interconnected mechanisms regulating target selective O-GlcNAcylation by OGA and OGT. Each dotted arrow represents higher-level crosstalk between the various regulatory mechanisms.

OGT structure and polypeptide acceptor specificity

OGT encodes a metal-independent CAZY (www.cazy.org) family GT41 β -*N*-acetylglucosaminyltransferase belonging to the GT-B superfamily of glycosyltransferases. This essential gene is located on the X-chromosome and encodes a modular protein composed of five distinct regions: i) an N-terminal region consisting of an isoform specific number of contiguous helix-turn-helix tetratricopeptide repeats (TPRs), ii) a transitional (H3) helix that sits between the N- and C-terminal halves, iii) a C-terminal region containing the GT41 catalytic domain with two catalytic lobes (Cat1 and Cat2) that each have a Rossmann fold, iv) an intervening domain with a topologically novel fold comprised of a seven stranded β -sheet core stabilized by flanking α -helices (IntD), and v) a putative C-terminal phosphatidylinositol-binding region (PPO) (Figure 2A). There are three different isoforms of OGT expressed in human cells that vary in the number of N-terminal TPRs. Nucleocytoplasmic OGT (ncOGT) has 13.5 TPR repeats, mitochondrial OGT (mOGT) has 9 repeats, and short OGT (sOGT) has 2.5 repeats (Figure 2A). These isoforms have distinct subcellular localization patterns and activities (see localization section below).

In 2011, the seminal crystallographic structure of human OGT was determined illuminating its unique atomic architecture. The structure comprises 4.5 N-terminal TPR repeats and the full C-terminal catalytic region in a ternary complex with UDP and a CKII peptide substrate (hereafter called hOGT_{4.5}) [4]. The TPRs in this structure (aa 313-400) overlap with an earlier OGT crystal structure consisting of 11.5 TPR repeats, and alignment of the two structures provides a putative model of the full-length protein (Figure 2B) [4]. The TPR superhelix consists of two layers of helices, an inner concave face formed by helix-A and an outer convex face formed by helix-B. Notably, helix-A has a highly conserved asparagine ladder that runs the length of the TPR domains that is involved in binding to peptide acceptors (see below) [4]. The C-terminal end of the TPR superhelix packs against the catalytic domain carving out a narrow acceptor peptide binding groove that feeds into the catalytic centre found at the interface of Cat1 and Cat2 [4]. The Int-D domain packs against the outer face of the Cat2 lobe oriented away from the active site core. The function of the Int-D domain remains unknown but in conjunction with a Cat2 helix, and the

C-terminal PPO, it forms a large electropositive surface comprising ten lysine residues that may be involved in ligand binding (see below) [4].

As an inverting glycosyltransferase, OGT catalyzes the formation of a β -glycosidic linkage between GlcNAc and the acceptor peptide serine. The peptide acceptor binds OGT predominantly through amide backbone hydrogen bonds with the β -hydroxyl group of its glycosylated serine projecting directly into the nucleotide sugar binding site. The peptide acceptor covers the solvent exposed face of the bound UDP-GlcNAc, effectively trapping it within the active site (Figure 3A). This observed binding mode in combination with kinetic data support the broadly accepted proposal that OGT catalyzes glycosyltransfer via an ordered bi-bi mechanism whereby UDP-GlcNAc must bind the active site first followed by the acceptor peptide [4]. Intriguingly, fundamental mechanistic details remain unknown, including the identity of general base responsible for deprotonating the catalytic serine [4]. Briefly as reviewed [4], three alternative general bases were proposed including His498, Asp554, or the α -phosphate of UDP-GlcNAc. Although mutation of His498 results in inactive enzyme, the side chain interactions suggest it is protonated at neutral pH making it poorly suited to serve as a general base. Direct transfer of a proton to α -phosphate of UDP-GlcNAc appears energetically unfavorable. Structural studies, however, revealed a series of ordered water molecules in the active site acting as a potential proton shuttle adjacent to Asp554 and functional studies reveal defective sugar transfer when this residue was mutated to asparagine, offering the best support for the identity of the general base to date.

OGT lacks a strict consensus sequence governing its activity. However, subtle sequence preferences help govern substrate selectivity. The specificity of OGT was assessed using a saturation library of 3,480 unique acceptor peptides displayed in a monolayer. As predicted by earlier work [5], valine and alanine were preferred in the -3 and +2 subsites. Additionally, a preference for aromatic residues in the -4 position was uncovered [6]. Notably, proline was previously shown to be preferred at the -2 subsite [5]. In contrast, proline at the +1 position has been found to prevent O-GlcNAcylation within certain peptides [7]. OGT predominantly glycosylates serine and threonine residues located within disordered regions on protein targets but also appears able to glycosylate residues positioned in a variety of different secondary

structures [8]. However, these secondary structures may need to be unfolded to be accommodated within the OGT active site. Although not yet characterized, such local unfolding may be triggered in response to various stimuli, or potentially occur during the co-translational O-GlcNAcylation of some nascent chains [9], prior to protein folding. The presence of other PTMs can also influence protein targeting as exemplified by the observation that acceptor peptide phosphorylation can reduce OGT catalyzed O-GlcNAcylation *in vitro* [7]. However, elucidating the physiological significance of this proposed PTM code awaits quantitative analysis of levels on endogenous proteins.

Emerging evidence shows that peptide binding occurs not just in the GT41 active site but also within the TPR domains. A protein microarray in conjunction with UDP-GlcNAz was used to establish OGT targeting of proteins using downstream click-chemistry to incorporate biotin [10]. This method was used to assess the catalytic contribution of a poly-asparagine ladder located within the TPR domains, known to engage in numerous bidentate hydrogen bonds with the peptide backbone of Tab1 [11] (Figure 3A). An OGT mutant construct consisting of alanine in place of these 5 asparagine residues (5N5A) retained activity toward short peptides but impaired modification of proteins [10], supporting the importance of these residues in indiscriminate recognition of the polypeptide backbone of proteins distant from the site of glycosylation. In a different approach, the Jiang group developed a GlcNAc electrophilic probe (GEP) that consists of a UDP-GlcNAc analog containing an allyl chloride electrophile extending as an N-acyl group from the 2-amino position [12]. This GEP was used to discern whether mutations in OGT affected sugar binding or protein acceptor binding and glycosylation by examining its relative partitioning to OGT (C917) or the acceptor protein. This method yielded results further supporting an important role for the asparagine ladder in acceptor protein binding [12]. Recently, the XLID OGT mutation, L254F, within the seventh TPR was found to distort the TPR superhelix resulting in reduced thermal stability and catalytic activity [13]. Furthermore, five additional mutations mapping to the OGT TPR domains have recently been correlated with XLID [13-15]. Very recently, two aspartate residues (D386 and D420) located in the OGT TPR lumen distal from the active site were shown to be important for substrate selection. Interestingly, mutation of these residues to alanine altered substrate specificity and increased rates of protein glycosylation *in vitro*. In

particular, a preference was found for substrates with a lysine or arginine positioned 7-11 residues away from the site of glycosylation [16]. Taken together, the OGT TPR domains are emerging as essential mediators of substrate binding, enzyme activity, and stability.

OGA structure and target specificity

OGA encodes two distinct splice variants referred to as long (OGA-L) and short (OGA-S) isoforms. Human OGA-L (hOGA) consists of three domains connected by disordered regions: i) an N-terminal *N*-acetyl- β -D-glucosaminidase catalytic domain (CAZy GH84) with a $[(\beta/\alpha)_8]$ triose-phosphate isomerase (TIM) barrel structure, ii) a helical bundle referred to as the stalk domain composed of four α -helices, and iii) a C-terminal pseudo histone acetyl-transferase (HAT) domain with a GCN5 acetyltransferase-like fold (Figure 2C). The pseudo-HAT domain lacks the conserved P-loop motif required for binding of the cofactor, acetyl-CoA, implying that it likely has a non-enzymatic function. OGA-S lacks the pseudo-HAT domain and part of the stalk domain, leading to greatly reduced enzyme activity.

Recently, three groups independently solved the long-anticipated crystal structure of hOGA. This was achieved by the systematic design of various constructs lacking disordered regions [17-19]. The homodimer is stabilized by a domain swapped helix (α 17: aa 676-694) [18,19]. Notably, a construct lacking this α 17 helix (residues 1-662) does not dimerize and displays 100-fold lower catalytic efficiency as compared to WT OGA in processing *p*NP-GlcNAc suggesting that dimerization is required for maximal activity [19].

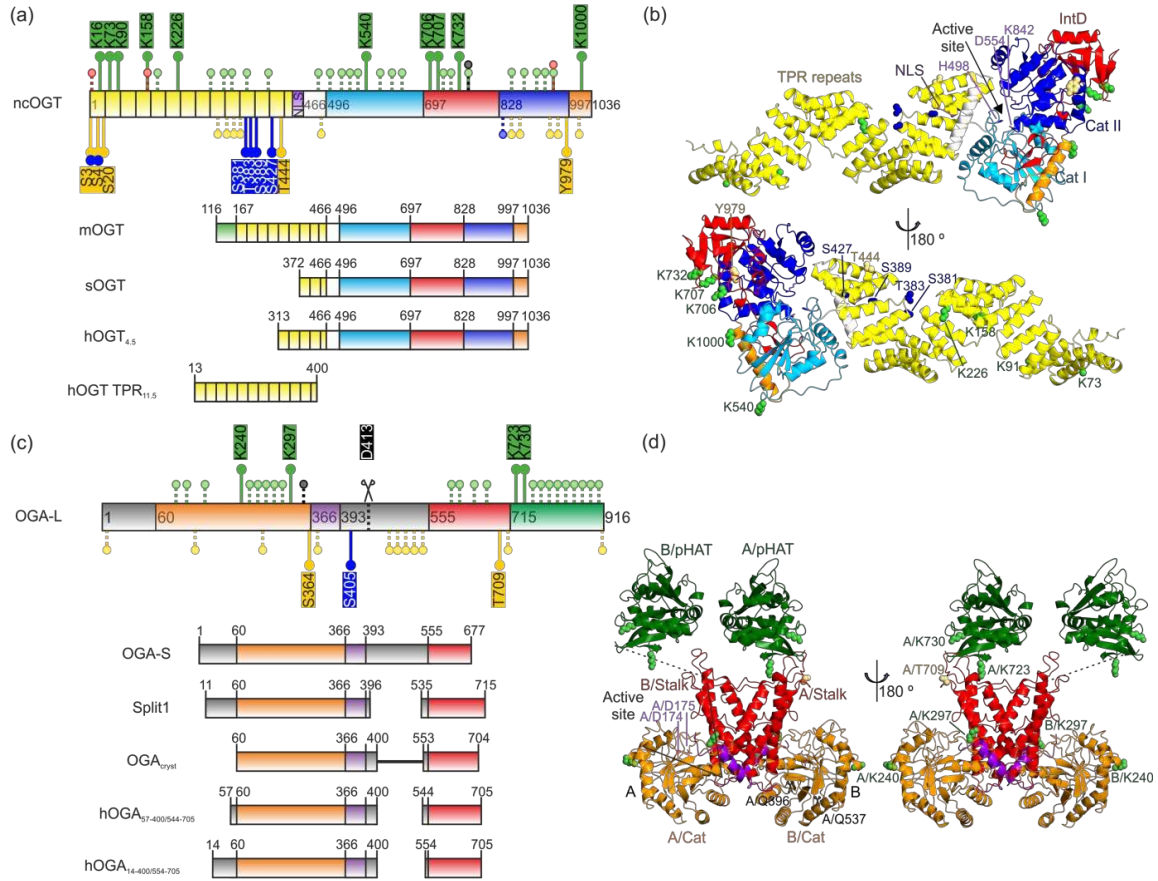


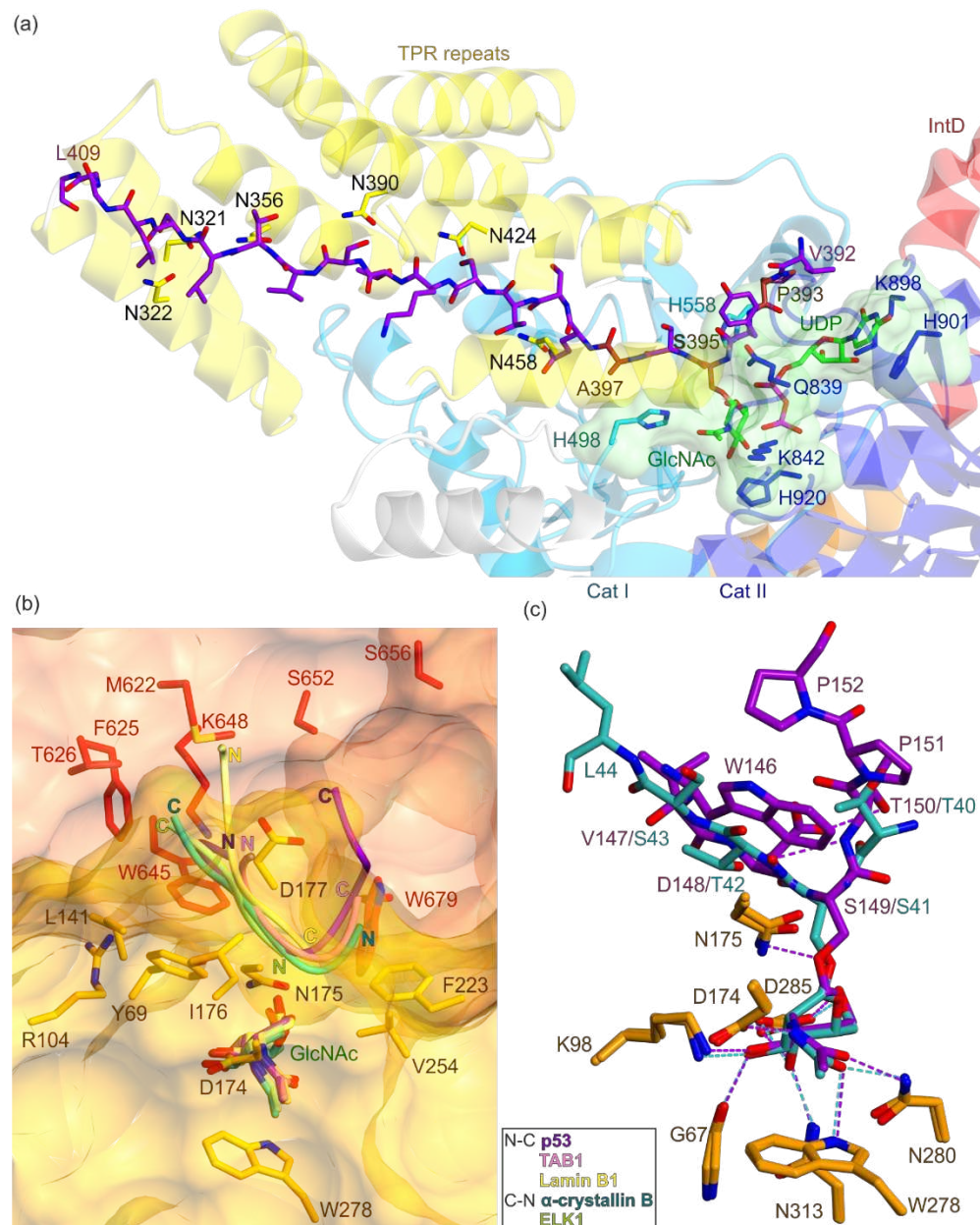
Figure 2. Domain structure and isoforms of OGT and OGA. A) Schematic of hOGT showing splice variants and constructs used for crystallography. OGT is found as three isoforms distinguished by the number of TPRs. The TPRs are shown in yellow, the NLS (D451-P453) is coloured purple, transitional helix (H3) is white, the glycosyltransferase catalytic domains are illustrated in light blue and dark blue, the Int-D (intervening domain) is red, and the phosphoinositide binding domain of OGT (PPO) is coloured orange with sequence numbered according to UniProtKB/SwissProt accession (P56558.1). In panels A and C, putative PTMs compiled using PhosphoSitePlus [20] are represented on ncOGT and OGA-L as follows: phosphorylation (yellow), O-GlcNAcylation (blue), ubiquitinylation (green), acetylation (red), and sumoylation (black). High confidence PTM sites with 5 or more references or experimentally determined by low-throughput mass spectrometry mapping methods are shown with solid lines and bold colours. Lower confidence sites with fewer than 5 references and determined by high-throughput methods are shown with dotted lines and light colours. B) Overall crystallographic model of ncOGT. The model was built by superposing hOGT_{4.5} (PDB ID: 3PE3) and hOGT TPR_{11.5} (1W3B). High confidence PTMs are labelled, as well as domains and key active site catalytic residues. C) Schematic of human OGA splice variants as well as constructs used for crystallography. Disordered regions are shown in black, the N-terminal GH84 domain is illustrated in orange, the helical bundle domain is purple, the C-terminal stalk domain is shown in red and the “pseudo HAT” domain is represented as a green cartoon. The caspase-3 cleavage site is indicated by scissors. D) Overall crystallographic model of hOGA. The hOGA Split1 crystal structure (PDB ID: 6HKI) is shown attached at the C-terminal end (Y715) to a homology model of the OGA pseudo-HAT domain constructed using Phyre2 from the *Oceanicola granulosus* homolog (PDB ID: 3ZJO, 29% sequence identity). Structures in B and D are colour coded as in A and C with high confidence PTMs labelled on the structures.

A V-shaped active site cleft ($\sim 22 \times 25 \text{ \AA}$ with an angle of $\sim 70^\circ$) is formed at the interface of the catalytic domain of monomer A and the stalk domain of monomer B [18] (Figure 2D). Multiple hOGA-glycopeptide bound structures reveal peptides bind within the cleft in either orientation [18,21,22] (Figure 3B-C). Two conserved aspartate residues flank the glycosidic bond, acting as general acid/base catalysts to facilitate a two-step catalytic mechanism involving a transient oxazoline intermediate [4]. Kinetic analysis of OGA mediated O-GlcNAc hydrolysis on intact proteins revealed that OGA indiscriminately cleaves diverse O-GlcNAc sites across different targets with roughly equivalent catalytic efficiency [23], an observation that is supported by the enzyme cleaving O-GlcNAc residues incorporated at “unnatural” sites [24]. This promiscuous substrate selectivity is likely in-part due to the predominant interaction of OGA with amide backbone atoms within the bound glycopeptide. As seen elsewhere [23], the rate of OGA catalyzed hydrolysis of an O-GlcNAcylated serine was shown to be reduced by half in the presence of an adjacent phosphotyrosine on a ZO3-derived model peptide (RESSYDIY_(p)RVPSS_(g)QS) [25]. The ability for PTMs to influence OGA catalyzed removal merits further investigation. In summary, recent research has provided a vital structural foundation for understanding OGA and OGT. The challenge for the future is to build upon this knowledge to uncover how regulatory factors modulate their structure and function to choreograph target specific O-GlcNAcylation.

Localization

The O-GlcNAc cycling enzymes adopt distinct subcellular loci during different phases of the cell cycle, in response to stimuli, and across cell types. The OGT and OGA isoforms (Figure 2) have long been known to display different subcellular localization patterns; ncOGT is found within the nucleus and cytoplasm, sOGT is predominantly localized to the cytosol, and mOGT is thought to be largely mitochondrial – though this is a topic of some debate [26,27]. OGA has two dominant splice variants with OGA-L being nucleocytosolic with preferential localization in the cytoplasm and the largely inactive OGA-S residing in the nucleus and on the surface of nascent

lipid droplets, where it is thought to regulate proteasome-mediated droplet remodelling (Figure 4A) [1].



peptides α -crystallin B (PDB ID: 5VVV) and p53 are shown in cyan and purple. Key hydrogen bond interactions are coloured according to peptide.

Excitingly, the molecular mechanisms regulating these isoform specific localization patterns are beginning to emerge. Recently, the ncOGT nuclear localization signal (DFP; residues 451-453), which is required for interaction with importin α 5 and subsequent translocation through the nuclear pore complex (NPC) (Figure 4A) was characterized [28]. mOGT is proposed, based on sequence analysis, to contain a putative N-terminal mitochondrial targeting sequence. Consistent with this hypothesis, OGT appears highly concentrated in the mitochondrial inner membrane where it interacts with electron transport chain complex IV and is suspected of O-GlcNAcylation of various mitochondrial proteins [29]. Curiously, the pyrimidine nucleotide carrier 1 transporter protein (SLC25A33) translocates UDP-GlcNAc from the cytosol to the mitochondrial matrix, potentially facilitating mOGT catalyzed mito-specific glycosyltransfer (Figure 4A) [29]. Isoform specific siRNA knockdown of mOGT leads to Drp1 dependant mitochondrial fragmentation, reduced membrane potential, and loss of mitochondrial content, supporting an important role for OGT in maintaining mitochondrial integrity and function [27].

In addition to these isoform specific localization patterns, overexpression of tagged O-GlcNAc cycling enzymes shows their partitioning to distinct subcellular locations during cell division and in response to signalling events. During mitosis, OGT is concentrated at the central spindle assembly during anaphase, and the midbody during cytokinesis. This is consistent with the formation of transient complex between OGT, OGA, mitotic Aurora kinase B (AURKB), and protein phosphatase 1 (PP1), which regulates vimentin filament glycosylation to control intermediate bridge formation and severing during cytokinesis (Figure 4B) [30]. Recently, localization of endogenously expressed O-GlcNAc cycling enzymes as well as global O-GlcNAcylation were investigated in bovine and human oocytes during meiosis by immunocytochemistry and confocal microscopy [31]. O-GlcNAcylated proteins were distributed throughout the nucleus and cytoplasm with enrichment at the nuclear envelope during prophase-I, whereas during metaphase O-GlcNAcylated substrates localized throughout the cytoplasm with slight enrichment at the cortex. OGA was localized at the cortex throughout

meiosis, whereas OGT was localized to the meiotic spindles [31]. These results support the idea that localization of the O-GlcNAc cycling enzymes is regulated during cell division. Despite having cell division-dependent localization patterns the mitotic and meiotic roles of the O-GlcNAc cycling enzymes remain poorly understood, though altering levels of these enzymes clearly affects cell division. Upon prolonged insulin stimulation of 3T3-L1 adipocytes, a subset of ncOGT is proposed to be recruited to the plasma membrane by phosphatidylinositol (3,4,5)-triphosphate (PIP3), to modulate the insulin signalling pathway by O-GlcNAcylation (Figure 4A) [32-34]. OGT was initially proposed to have a PIP3 binding site located in the C-terminal catalytic and Int-D domains, however, this topic remains controversial [4]. We speculate that this type of triggered localization of the O-GlcNAc cycling enzymes may be relatively common to enable temporal control of O-GlcNAc levels at distinct subcellular locations. Yet, the molecular bases for these changes need more focused biochemical studies combined with cell-based experiments.

Finally, OGT displays cell type specific localization patterns. For example, OGT is enriched in the postsynaptic density of excitatory synapses perhaps to enhance the O-GlcNAcylation of multiple proteins as seen to occur upon neuronal stimulation. Postsynaptic KO of OGT decreases synaptic expression of ionotropic transmembrane glutamate receptor AMPA subunits (GluA2 and GluA3), reduces presynaptic terminals, and stunts the development of mature dendritic spines [35]. Future discovery-based investigations to systematically catalogue OGA and OGT localization patterns across diverse cell types and in response to varied stimuli would likely be illuminating, as has been the case for kinases and phosphatases.

Post-translational modifications

The O-GlcNAc enzymes are decorated with numerous PTMs. In fact, a survey of the PhosphoSitePlus database reveals that proteomic discovery-based mass spectrometry efforts have uncovered a total of 55 and 42 distinct PTMs on human OGT and OGA (Figure 2) [20]. For OGT, a handful of these PTMs have been ascribed functions including dynamic fine-tuning of its localization, turnover, and substrate specificity (Table 1). O-GlcNAcylation of OGT Ser389 within TPR12 enables its nuclear localization [28]. Similarly, AMPK mediated phosphorylation of Thr444 contributes to OGT nuclear import in myotubes [36]. We note that the T444 and S389

phosphosites are both located within TPR12 in proximity to the recently characterized NLS (451-453), and thus may regulate recruitment of the nuclear import machinery. This NLS is present in all OGT isoforms, however, its contribution to nuclear import has only been investigated in ncOGT. Phosphorylation of OGT T444 changes its substrate selectivity *in vitro* and in proliferating HEK293T kidney cells, and alters its binding partners. T444 phosphorylation thus appears to regulate OGT target specificity, localization, and protein-protein interactions – phenomena that are likely not mutually exclusive. Upon glucagon-induced calcium signaling, calcium/calmodulin-dependant kinase II (CamKII) phosphorylates OGT S20, which alters the specificity of OGT to promote O-GlcNAcylation and activation of the Ulk proteins involved in autophagic induction [37]. Similarly, Checkpoint kinase 1 (Chk1) also phosphorylates Ser-20, and this event was separately found to stabilize OGT against proteasomal degradation and be required for its previously mentioned localization to the midbody upon cytokinesis (Figure 4B) [38]. Understanding the roles of OGT phosphorylation may yield insight into its stimulus-induced spatiotemporal regulation. Even less explored are the multiple putative ubiquitylation sites discovered on OGT in proteome-wide mass spectrometry experiments (PhosphoSitePlus database [20]). For example, the LSD2 histone demethylase acts as an E3 ligase and targets OGT for polyubiquitylation at an unknown site, thereby promoting its proteasomal degradation [39], whereas the BAP1 deubiquitinase protects OGT against UPS mediated degradation [40]. However, the identities of the E1 and E2 enzymes regulating these UPS mediated degradation pathways remain unknown.

PTMs can also directly modulate OGT catalyzed glycosyltransfer. OGT can be phosphorylated at S3 and S4 by glycogen synthase kinase 3 β (GSK3 β) [41]. Interestingly, GlcNAc has also been identified on OGT S3 and S4 suggesting the possibility that O-GlcNAcylation and phosphorylation may antagonize each other at this site [41]. Although an appealing hypothesis, O-GlcNAc and phosphorylation are both most often substoichiometric and, accordingly, such proposed direct reciprocal crosstalk has been difficult to clearly demonstrate as this would require quantitative assessment of PTMs on endogenous proteins. Taken together, the roles for PTMs in controlling OGT localization, turnover, and activity are slowly emerging. The challenge for the future is to confirm these effects, decode the combinatorial influence of these diverse

PTMs on OGT function in response to subcellular signalling, and delve deeper into the structural and biochemical basis behind these observations.

OGA is also heavily decorated with PTMs, however very little is understood regarding their functional ramifications. During apoptosis, OGA is cleaved by caspase-3 within a non-canonical S₄₁₀VVD₄₁₃ recognition site [42]. Co-expression of the two caspase-3 cleavage products recapitulates OGA activity in cells, suggesting the two halves remain associated within cells. However, a functional role for this cleavage has not been defined. Studies have reproducibly identified GlcNAc at S405, yet it is not known whether this modification has a functional role [20]. Bearing in mind that individual sites of modification do not necessarily have physiological roles, identifying those which do and exploring how some of these post-translational events influence OGA function will bridge a key gap in our understanding of the regulation of O-GlcNAc.

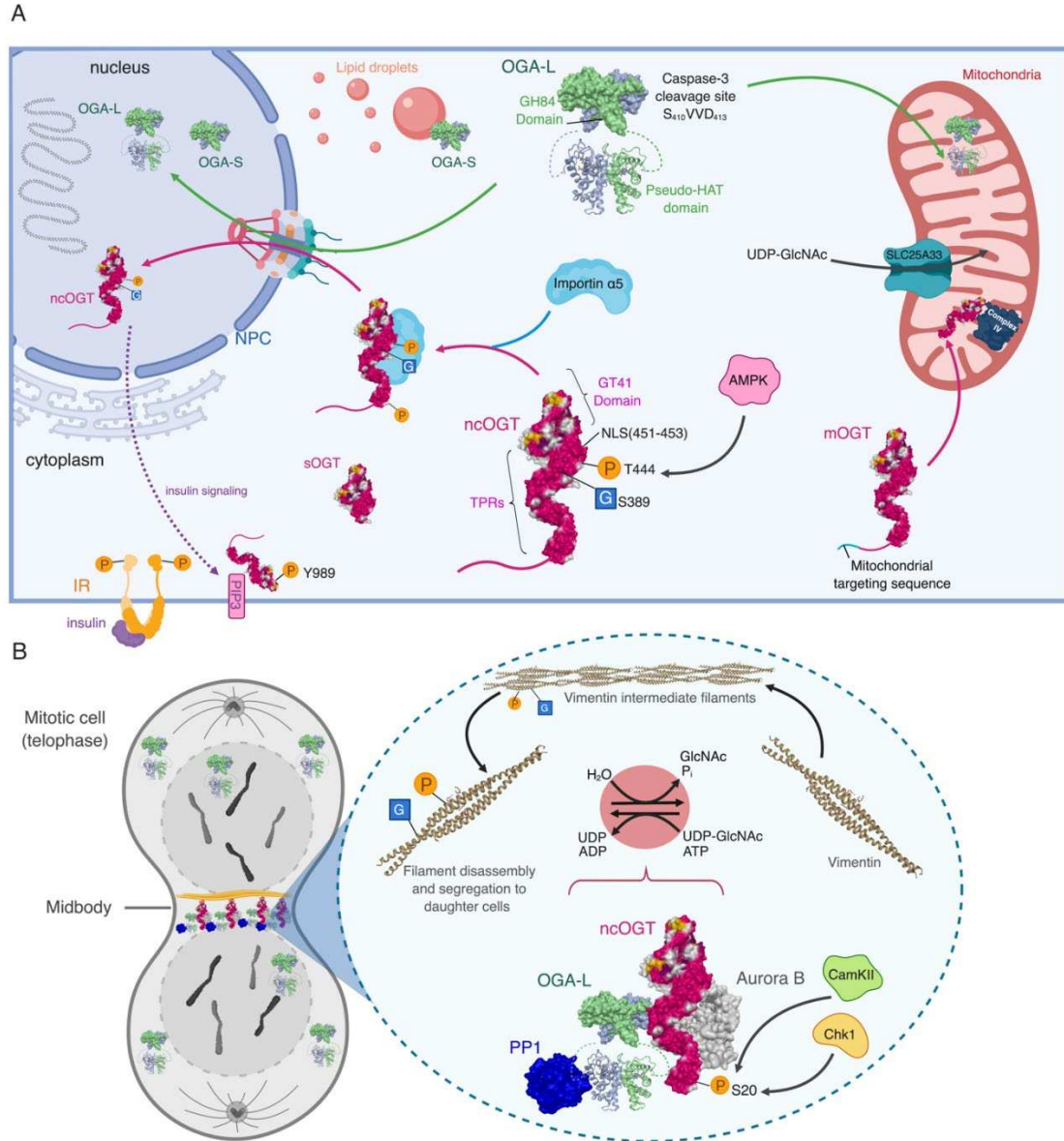


Figure 4: Modulation of OGA and OGT localization by PTMs and protein binding partners. A) Subcellular localization of OGA and OGT. Importin $\alpha 5$ facilitates the nuclear import of ncOGT and this process is dependent upon S389 O-GlcNAcylation and AMPK mediated T444 phosphorylation. The OGT-S isoform is predominantly cytosolic. OGA-L localizes to the cytosol and nucleus, and OGA-S exists in the nucleus and on the surface of lipid droplets. OGA-L and mOGT localize to the mitochondria, and mOGT associates with complex IV. **B)** OGT and OGA localization and complexation during mitosis. OGT is localized almost exclusively to the midbody during mitosis. In contrast, OGA localizes diffusely throughout the cell. OGT, OGA, AURKB, and PP1 are thought to form a complex at the midbody during mitosis. This complex modulates vimentin intermediate filament formation and disassembly, thereby regulating segregation of daughter cells during cytokinesis. We note that structural details regarding the (OGT, OGA, AURKB, PP1) complex remain unresolved, therefore, our representation of this complex in panel B is for illustrative purposes only.

Interaction partners

Interaction partners play an integral role in modulating the activity and localization of the O-GlcNAc cycling enzymes. Here, we focus on select recent examples germane to the regulation of O-GlcNAc. The nuclear receptor REV-ERB α integrates the circadian clock with both glucose and lipid metabolism and has recently been shown to interact with and modulate OGT [43]. REV-ERB α shields cytoplasmic OGT from proteasomal degradation and appears to enhance OGT catalytic activity in the nucleus, thereby increasing O-GlcNAcylation of proteins within both compartments. For example, REV-ERB α is proposed to promote OGT-mediated regulation of insulin signalling by boosting O-GlcNAcylation of AKT in the cytoplasm [43]. Thus, REV-ERB α exerts pleiotropic circadian activities through direct interaction with OGT.

UDP-*N*-acetylglucosamine pyrophosphorylase-1 (UAP1) catalyzes the last step in the synthesis of UDP-GlcNAc. A UAP1 paralog, UAP1-like-1 (UAP1L1), is required for OGT mediated protein O-GlcNAcylation in HepG2 liver hepatocellular carcinoma cells [44]. Surprisingly, UAP1L1 does not efficiently catalyze UDP-GlcNAc synthesis, but instead interacts directly with the C-terminal catalytic domain of OGT. Knockdown of UAP1L1 markedly reduced global O-GlcNAcylation in HepG2 and TONG cells, yet UAP1L1 alone is not sufficient to bolster OGT activity *in vitro* [44]. Thus, UAP1L1 likely maintains OGT activity within cells through direct binding, though more detailed characterization is necessary.

5-methylcytosine (5mC) in DNA plays important roles in transcriptional regulation, genomic imprinting, and suppression of transposable elements. The TET1-3 (Ten Eleven Translocation) proteins oxidize 5mC and thereby facilitate reversal of locus specific DNA methylation particularly within promoter regions [45]. Though sometimes contradictory, a range of studies have shown OGT binds to TET proteins and regulates their activity (reviewed in, [46]). Sadly, aside from the work on REV-ERB α [43], this promising area has largely languished since 2015 and a challenge for the future is to better determine the context-dependant effects of these interactions on chromatin structure and gene regulation.

To identify putative OGA binding partners, BioID proximity biotinylation in combination with stable isotope labeling of amino acids in cell culture (SILAC) was used [47]. This analysis

revealed 90 proteins displaying stress-dependant interactions with OGA. OGA interactions with fatty acid synthase (FAS), filamin-A, heat shock cognate 70 kDA, and OGT were verified by co-immunoprecipitation. *In vitro* analysis of the pool of OGA bound to FAS revealed it had only ~15% of the activity of free enzyme, and FAS overexpression appeared to boost oxidative stress-induced global O-GlcNAc levels in cells [47]. Overall, the structural and biochemical features governing these protein-protein interactions remain unexplored and limit our understanding of how binding partners functionally regulate OGT and OGA.

Table 1

Key post-translational modifications and processing events on OGT and OGA

Protein (residue)	Modification	Functional role	Enzyme(s)	Ref.
OGT (S3)	Phosphorylation, O-GlcNAc	Increases activity	GSK3 β	[41]
OGT (S4)	Phosphorylation, O-GlcNAc	Increases activity	GSK3 β	[41]
OGT (S20)	Phosphorylation	OGT activity / mitotic localization	Chk1, CamKII	[37,38]
OGT (S389)	O-GlcNAc	Required for nuclear localization	OGT	[28]
OGT (T444)	Phosphorylation	Nuclear uptake and activity	AMPK	[36]
OGT (D451-P453)	Nuclear localization signal	Nuclear uptake	*N.A.	[28]
Ψ OGT (Y989)	Phosphorylation	Increased activity	IR, Src	[32]
OGA (S364)	Phosphorylation	Unknown	Unknown	[20]
OGA (S405)	O-GlcNAc	Unknown	Unknown	[20]
OGA (S410-D413)	Proteolysis site	Unknown	Caspase-3	[42]

*N.A. means “non-applicable”

Ψ Speculative modification proposed based on blots and sequence analysis on rat OGT Y979 (hOGT Y989)

Metabolic Regulation

The concentration of the UDP-GlcNAc donor substrate used for OGT catalyzed glycosyltransfer is responsive to nutrient flux due to the direct dependency of HBSP on major cellular metabolites. In particular, intracellular concentrations of glucose, glutamine, fatty acids, and GlcNAc modulate HBSP flux and UDP-GlcNAc abundance (for an early perspective see [48]). Notably, HBSP enzyme expression and allosteric modulation are under tight control and respond to various changes in nutrient and metabolite abundance and intracellular signalling (reviewed

in [49]). For example, the unfolded protein response (UPR) signal transducer, spliced X box-binding protein 1 (XBP1), acts as a transcriptional activator to induce expression of rate-limiting HBSP enzymes boosting cellular O-GlcNAcylation in response to ER stress [50]. While nutrient supply clearly alters UDP-GlcNAc levels, nutrient flux may also induce intracellular signalling pathways that ultimately modulate the abundance and function of the O-GlcNAc cycling enzymes. Accordingly, while generally accepted in the field, the effects of nutrients on regulation of O-GlcNAc have surprisingly not been systematically investigated to simultaneously monitor UDP-GlcNAc levels, levels of HBSP enzymes, OGA and OGT, and downstream levels of O-GlcNAc. Such studies would help provide a solid foundation to systematically assess the functional and mechanistic basis for the effects of nutrients.

Transcriptional activation and repression

New findings are emerging to support expression of OGA and OGT being coordinately regulated by control of transcriptional programs that work to maintain balanced O-GlcNAc levels. For example, increases in OGT lead to concomitant increases in OGA expression, and vice versa, in what appears to be an effort to buffer the cell from rapid changes in O-GlcNAcylation. Furthermore, treatment of cells with the selective OGA inhibitor ThiametG, boosts O-GlcNAc levels and induces a compensatory increase in OGA gene expression and a correlated decrease in OGT abundance [51], and the converse is also true for OGT inhibitors [52].

We are just beginning to uncover transcriptional programs governing these coordinated shifts in expression of *OGT* and *OGA*. For example, OGA serves as a co-activator in conjunction with the histone acetyltransferase p300 to positively regulate transcription factor CCAAT/enhancer-binding protein beta (C/EBP β) – among the most common activators occupying the *OGT* promoter (Figure 5) [53]. This transcriptional regulatory mechanism enables OGT expression to be tuned to OGA levels to balance O-GlcNAcylation. Additionally, the *OGA* promoter is sensitive to OGT expression as exemplified by a recent analysis of O-GlcNAcylation in XLID patients. An XLID variant L254F-OGT, results in reduced L254F-OGT protein levels in isolated patient lymphoblastoid cells [3]. However, global O-GlcNAc abundance appeared unaltered, presumably due to a compensatory decrease in OGA mRNA and downstream OGA

levels. OGT appears to be involved in a balancing mechanism that regulates global O-GlcNAc levels in XLID through formation of an OGT-mSin3A-HDAC1 repressive complex at the *OGA* proximal promoter region (Figure 5) [3]. Curiously, E2F transcription factor 1 (E2F1) concurrently represses transcription at both *ogt* and *oga* promoters in a retinoblastoma (Rb1)-dependant manner in mice to maintain a balanced mRNA pool (Figure 5) [54]. *OGT* transcription also appears to be regulated by hepatocyte nuclear factor 1 homologue A (HNF1A), which is itself O-GlcNAc modified. Loss of O-GlcNAc appeared to increase transcription of *OGT*, suggesting a mechanism for autoregulation of O-GlcNAc homeostasis [55]. Overall, a higher order network of multiple transcriptional mechanisms likely act in concert to maintain O-GlcNAc homeostasis but decoding this will require both more detailed biochemical and system wide studies.

Transcription of O-GlcNAc cycling enzymes is also dysregulated in response to other specific stimuli. For example, OGT levels are markedly increased in human papillomavirus (HPV) induced cervical neoplasms, and transfection of HPV oncogenes into mouse embryonic fibroblasts induces a pronounced increase in OGT mRNA and protein levels [56]. HPV infection alters the expression of several transcription factors with predicted binding sites within the *OGT* promoter. Overexpression of transcription factors AP-1, SP-1, NF- κ B, p65, and c-MYC enhanced OGT promoter activity on a reporter construct [56]. However, further *in vivo* analysis of the relative contribution of these transcription factors to enhancement of endogenous *OGT* expression is required. As an additional example, upon lipopolysaccharide stimulation, E2-related factor – 2 (Nrf2) binds the *ogt* promoter and enhances its transcription in bone-marrow derived mouse macrophages, resulting in amplified O-GlcNAcylation and inhibition of pro-inflammatory transcription factor STAT3. Interestingly, Nrf2 is not required for baseline OGT expression but rather only boosts its abundance in response to stimuli. Furthermore, the E3 ubiquitin ligase CUL3 negatively regulates OGT expression through its targeted degradation of Nrf2 (Figure 5) [57]. Future efforts should aim to uncover additional *cis*- and *trans*-acting factors controlling transcription of *OGT* and *OGA* and illuminate how they are integrated to tailor transcriptional programs in response to various stimuli.

Post-transcriptional regulation

transcriptionally repressed by the OGT-mSin3A-HDAC1 complex. The OGT mRNA transcript contains a retained fourth intron with an O-GlcNAc sensitive internal splicing silencer (ISS). In conditions of high O-GlcNAc the ISS prevents splicing of the detained intron leading to nuclear degradation of the transcript, whereas low O-GlcNAc results in splicing of the intron and subsequent nuclear export. The cytoplasmically-localized mature OGT and OGA mRNA transcripts are either translated into protein product or can be targeted for degradation via hybridization to miRNAs and subsequent RNA-induced silencing. OGT and EZH2 take part in a negative feedback mechanism to repress the miRNA-101 promoter.

stress responsive miRNA-200a and miRNA-200b antagonize the *OGT* mRNA transcript in conditions of high glucose in human aortic endothelial cells [59,60]. Recently, miRNA-101 has been found to target the transcripts of both *OGT* and *EZH2* for degradation. Interestingly, OGT mediated O-GlcNAcylation has been proposed to stabilize EZH2 thereby promoting EZH2 catalyzed histone H3K27 trimethylation within the miRNA-101 promoter. Because the H3K27me3 mark transcriptionally silences miRNA-101, a negative feedback mechanism that promotes metastatic colorectal cancer may operate (Figure 5) [61]. Finally, in hepatocytes, new data shows HCV infection induces miRNA-501-61p binding to the 3'UTR of OGT transcripts, blocking translation and leading to decreased OGT levels [62]. Moreover, this last observation is recapitulated bi-directionally using OGA and OGT inhibitors. On balance, miRNA mediated degradation is emerging as a key mechanism regulating context dependant fine control of expression of O-GlcNAc cycling enzymes.

Another post-transcriptional mechanism controlling OGT expression is the regulated splicing of its fourth intron, through the recently recognized phenomenon of retained introns (RI) [63]. High cellular O-GlcNAc levels are correlated with increased abundance of the RI spliceoform of the *OGT* transcript (OGT-RI) within the nucleus. Notably, pharmacological inhibition of OGT reduced OGT-RI levels, which correlated with enhanced OGT expression [63]. Furthermore, a 526-nts O-GlcNAc sensitive intronic splicing silencer (ISS) located within the fourth intron regulates abundance of this non-translated spliceoform (Figure 5) [63]. Currently, the cellular fate of the OGT-RI, and the trans-acting factors that bind and regulate the ISS in response to fluctuating O-GlcNAc levels represent major unknowns of high interest.

Conclusion

In summary, recent crystallographic investigations of OGT and OGA have provided a structural foundation for understanding the molecular mechanisms regulating O-GlcNAc cycling. Upon exploring the current state of knowledge about these mechanisms, we emerge with a view that an interconnected network of regulatory factors dynamically tailors the abundance, localization, and activity of the O-GlcNAc cycling enzymes. For example, PTMs and protein interaction partners can exert pleiotropic effects on the localization and activity of OGT and OGA (Figure 5). Pre-translational regulatory mechanisms are emerging as major factors orchestrating global O-GlcNAc homeostasis. Additionally, nutrient-based regulation plays defined roles as well, both through modulation of these processes and by directly regulating levels of donor sugar substrates. While many new regulatory processes are emerging, understanding of events at the atomic level remains largely unknown. A major challenge is to integrate cell and tissue-based discovery studies with quantitative biochemical analyses to uncover the detailed molecular and atomic basis for regulation of O-GlcNAc. Such findings will illuminate how these events are antagonistic or synergistic in coordinating both global and target specific O-GlcNAcylation to meet cellular needs. Finally, given that O-GlcNAc is emerging as a druggable pathway, delving deeper to uncover these mysteries will likely enable targeted therapeutic approaches that modulate O-GlcNAc for human benefit.

Conflict of interest statement

DJV is cofounder of and holds equity in the company Alectos Therapeutics. DJV serves as CSO and Chair of the Scientific Advisory Board (SAB) of Alectos Therapeutics. GJD serves on the SAB of Alectos Therapeutics. DJV may receive royalties from SFU for commercialization of technology relating to OGA inhibitors.

Acknowledgements

This work was supported by grants from the Canadian Institutes for Health Research (CIHR) (D.J.V., PJT-148732, PJT-156202) and the Natural Sciences and Engineering Council of Canada (Discovery-RGPIN298406). D.J.V. is a Tier I Canada Research Chair in Chemical Biology. D.T.K. is supported by a postdoctoral fellowship from CIHR and a Trainee Award from the Michael Smith

Foundation for Health Research (MSFHR). G.J.D is a Royal Society Ken Murray Research Professor. A.M. is supported by the Biotechnology and Biological Sciences Research Council (BBSRC BB/M011151/1).

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

*of special interest

** of outstanding interest

- **[3] An important paper in the field. The authors provide unambiguous evidence for mutations in *ogt* implicated in XLID influencing OGT function. Despite largely normal global O-GlcNAc levels, significant changes in gene transcription are observed. Furthermore, a compensatory mechanism to maintain global O-GlcNAc levels involving OGT-mSin3A-HDAC1 dependant transcriptional repression at the OGA promoter is proposed.
- *[6] The authors develop a systematic platform for glycosylation sequence characterization and optimization and use this method to characterize OGT sequence preference. This analysis revealed a surprising preference for an aromatic residue at the -4 subsite.
- *[10] An asparagine ladder in the TPR domains mediates OGT interaction with protein substrates.
- * [12] New chemical biology tools to identify features of OGT responsible for substrate targeting. This method uncovered a patch of residues lining the inner surface of the N-terminal domain that contribute to interaction with multiple substrates.
- **[13] A nice structural study defines the effect of XLID-associated OGT mutation L254F as distorting the TPR helix.
- * [27] mOGT was shown to be catalytically active *in vivo* and plays an important role in supporting mitochondrial structure and function.
- **[28] A fundamental advance in discovery of the OGT NLS and the effects of S389 O-GlcNAcylation and interaction with importin α 5 for nuclear import.
- *[35] The authors demonstrate that OGT is enriched in the post-synaptic density of excitatory neuronal synapses whereby it regulates synapse maturation.
- *[37] Upon glucagon-induced calcium signalling CamKII phosphorylates OGT at S20, which induces O-GlcNAc modification of Ulk proteins through potentiation of AMPK-dependant phosphorylation.
- **[38] Chk1 phosphorylates OGT S20, and this modification regulates OGT localization to the mid-body and regulation of vimentin bridge formation and severing during mitosis.
- *[39] LSD2 was shown to act as an E3 ligase to ubiquitinylate OGT and thereby facilitate its UPS mediated degradation.
- **[43] Circadian nuclear receptor REV-ERB α was found to form a stable complex with OGT and regulate OGT-controlled processes in both the cytosol and nucleus.
- *[44] The authors characterize UAP1L1 as a novel OGT binding partner that is necessary for O-GlcNAcylation in cells.
- **[47] This study leverages BioID proximity biotinylation to identify 90 OGA-interaction partners including FAS, which when bound causes a substantial reduction in OGA catalytic activity.
- ** [52] The authors report the structure based evolution of OGT inhibitors with nanomolar affinity. Moving forward, these inhibitors may provide a key tool to facilitate discovery and targeted studies of O-GlcNAc in cells.

- *[53] This study demonstrates that OGA acts in conjunction with histone acetyltransferase p300 to positively regulate transcription factor C/EBP β , which acts as a transcriptional activator at the *ogt* promoter.
- * [57] Nrf2 was demonstrated to bind the *ogt* promoter and enhance transcription. Furthermore, E3 ubiquitin ligase CUL3 negatively regulates *ogt* transcript through targeted degradation of Nrf2.
- * [61] The authors demonstrate that miRNA-101 targets degradation of both OGT and EZH2. Furthermore, OGT and EZH2 catalyze O-GlcNAcylation and H3K27 trimethylation within the miR-101 promoter providing a negative feedback mechanism that transcriptionally silences miRNA-101.
- **[63] An exceptional finding. Retention of the OGT fourth intron is sensitive to global O-GlcNAc levels. Furthermore, this retained intron contains an ISS that regulates its splicing – by what mechanism remains a tantalizing mystery.

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